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MICROINJECTION EVALUATION OF A DIAMOND TURNED DIFFRACTION OPTICAL ELEMENT

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Abstract. *This work investigated the injection molding process of micro diffractive optical element in polymethylmethacrylate (PMMA), machined on electrolytic copper insert by single point diamond turning. One type of microstructure feature was selected in this study, namely: wavefront sensor. The replication fidelity was evaluated in terms of dimensional micrometric features found in the microstructure and the surface finish. An optical profiler and scanning electron microscopy were used to assess the machined inserts and the replicated features. The machined surfaces presented very low surface finish in the range of 16 nm Rms. Injection temperatures and pressures were varied between 85 °C / 130 °C and 70 bar / 130 bar, respectively. The influence of these parameters on performance of the replication process was assessed. The quantitative assessment of the replication was made by using a parameter called degree of replication which defines the ratio between the nominal height of the microstructure in the insert and the height of the microstructure in the polymer replica. The wavefront sensor presented the best degrees of replication: 98% and 99%, respectively. The experimental results showed that injection molding process is a viable technique to replicate high quality micro features of optical diffraction elements generated by single point diamond turning.*

Keywords: *Diamond tool, Diffractive optical elements, Micro injection, Fidelity of replication.*

1. INTRODUCTION

The fabrication of microstructures is closely related to the manufacture of microcomponents using replication techniques. For many applications, a large-scale reproduction of microstructures and microlenses can be made possible by techniques of cold molding, thermoforming and microinjection (Blasi et al, 1999; Brinskmeier and Preuβ, 1999; Piotter et al, 2000). The microinjection molding process allows playback of polymer microstructures, ceramic and metal (Brinskmeier and Preuβ, 1999; Piotter et al, 2002a). The molds require a high degree of surface finish, especially for optical applications. A decisive factor for the quality of the optical components is injected using molds and inserts manufactured using technology ultraprecision turning tool with monocrystalline diamond, where small components can be produced (diameter 1-5 mm), accurately so < 1 µm and roughness Ra <10 nm. This requires technical evaluation of micro and / or macrophotography offering capacity to measure tolerances and ensure the requirements of the project components. Techniques such as scanning electron microscopy (SEM) (resolution < 1.2 nm), laser interferometers (resolution < 1nm), atomic force microscopy (AFM) (resolution 0.1 nm) are examples of techniques widely applied in years.

A mold design generally follows a set of requirements that may be imposed by the injection equipment, the geometry of the parts to inject the desired number of impressions, among others. In injection molding, the overall goal is to produce the mold and its components in such a way as rigid as possible, in an attempt to find acceptable alignment and adjustment of all parts. The correct specification and implementation of strict manufacturing tolerances (parallelism, roughness, roundness and concentricity) are required for the mold meets these criteria. In the micro injecting the magnitude of these tolerances significantly decreases, which makes it problematic to manufacture the individual components of the mold, according to the geometrical and dimensional deviations that may occur. For example, a tolerance of 2.54 mm parallel on a conventional injection mold can be considered very accurate, but this micro injection quantity may be greater than micro component considered This work investigates techniques through numerical analysis, and experimental injection molding of micro lenses in polymeric material (PMMA), where the application of techniques for characterization of surfaces is also focused, to evaluate the manufacturing process of the mold and optical elements obtained in terms of accuracy of shape and surface integrity, considering the generated surface.

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2. EXPERIMENTAL PROCEDURE

The Fig.1 shows the detailed design and lens with circular structure with a diameter of 8 mm.

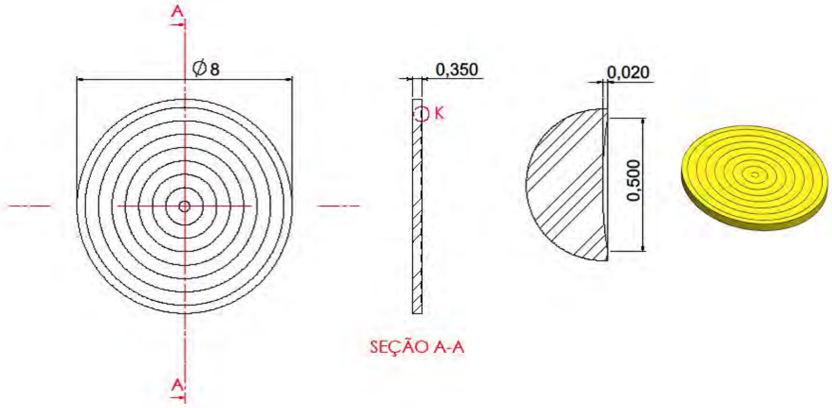
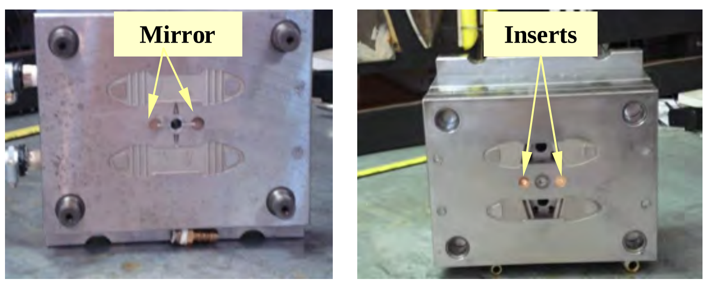


Figure 1. Circular lens

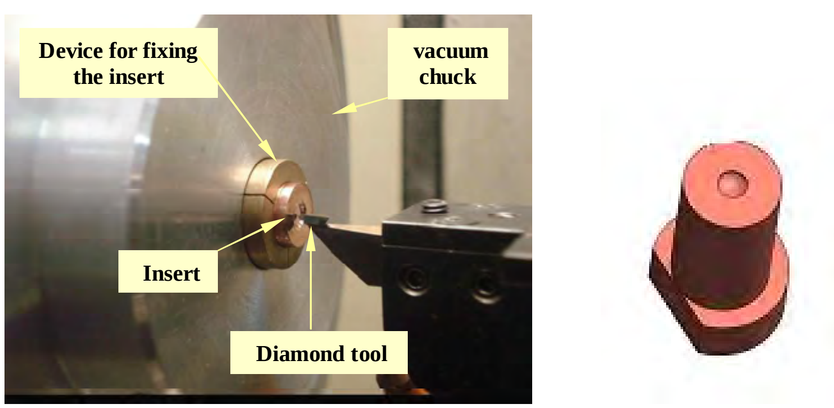
The lenses were made of polymethylmethacrylate (PMMA), whose trade name is Plexiglas ® V825, manufactured by Altuglas International. The polymer molding has the form of small granules, regular, usually cylindrical, with a diameter of 2 mm x 3 mm length. Aiming to minimize the time spent to construct the mold components, we used a set of brand Polimold, Model 1520 4 1 3 1 5A, plates, top and bottom are shown in Fig. 2 with their respective channels and inserts.



(a) (b).

Figure 2. Detail of the upper plates (a) and bottom (b).

Except cavities, inserts were machined in conventional lathe. The lens profile inserts was performed on the machine generating aspheric surfaces brand Ranko Pneumo, ASG model 2500, equipped with computer numerical control, Allen-Bradley 8200 CNC model. When machining of the inserts, Fig. 3 (a) and (b) we used a single crystal diamond tool, brand Contour Fine Tooling, HCO 10 m LGC model. The cutting fluid used was Alkalisol 900, a synthetic oil with water soluble function directed lubricate and cool mist formed on the workpiece / tool. The room temperature was kept constant at 21 ± 0.1 ºC.



(a) (b)

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Figure 3. (a) Machining of the inserts (b) Insert machined

The ultraprecision machining with diamond tool is a widely used process for the manufacture of molds for optics. With this process optical surfaces can be made without subsequent polishing. The precision of the geometry of the surface of a lens is essential for its optical performance. The deviation of the molded surface to the surface of the design will introduce unwanted aberrations in an optical assembly. In this work the inserts were made of electrolytic copper for high conductivity. The Tab. 1 shows the cutting parameters and tool geometry used in turning inserts.

Table 1. Parameters used in the turning insert

Tool	Rake angle γ^0	Nose radius (mm)	Spindle rotation (rpm)	Feed rate (μm)	Depth of cut (μm)
HCO 10m LGC	0	0.10	1000	1	1

The structure studied is composed of concentric rings with the application device wavefront sensor with cylindrical symmetry for measuring optical aberrations also known as Castro sensor which patent PI0201535 (Schor et al, 2002). It can be seen in the schematic drawing Fig. 4 example of this circular micro structure

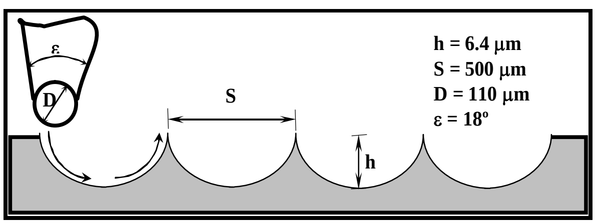
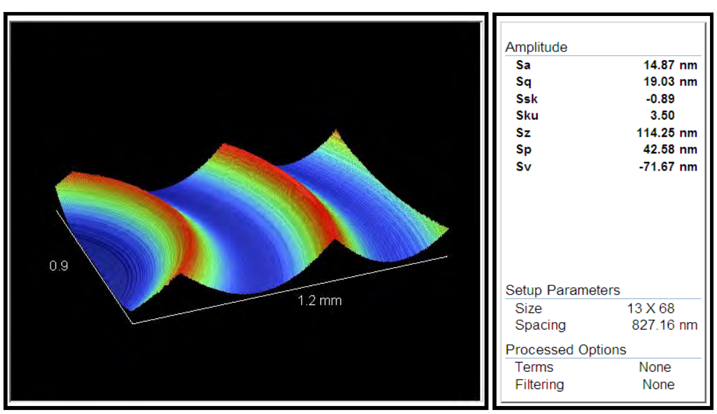
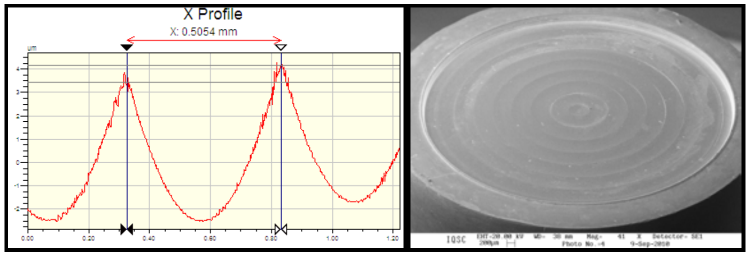


Figure 4. Schematic drawing of the circular profile microstructure.

Figure 5(a) shows the profilometry of 3D insert circular structure machined monocrystalline diamond tool. In (b) the value of the roughness on the insert Sa = 14.87 nm indicates that the machining process was well executed according to the machining conditions predetermined. In (c) shows the profile accuracy of this structure was obtained from the machining operation, taking as an example referring to the pitch size S, whose design value is 500 μm. The difference compared to the machined surface was 5μm.



(a) (b)



(c) (d)

Figure 5. (a) 3D image of circular microstructure. (b) Values of the roughness Sa.
(c) Profile structure showing the step value of the circular channel. d) SEM of the cavity machined.

The equipment used in molding, manufactured by Dr. Boy GmbH & Co. KG is a horizontal injection molding machine, 22M Series, which meets the needs of the production process intended and whose main features are: Clamping force: 220 kN. Screw diameter injection: 18 mm, maximum injection force: 65.82 kN. The injection molding machine operates in clean room, with an average temperature of 23 °C and relative humidity between 40 and 50%. The volume and the weight of the micro lens made concluded that to achieve a minimum amount acceptable for use of injection equipment should be created two cavities respectively fed by two primary distribution channels. The sprue channel and the cold well also had to be relatively massive compared with the feed cavities.

The Tab 2 shows the theoretical analysis parameters generated in the SolidWorks program concerning the utilization efficiency of the material, where it is found that the volume of the lens is less than 2% of the total molding

Table 2. Evaluation of the effectiveness of the material used in molding, in terms of weight and volume

Workpiece	Volume (cm^3)	Weight (g)	Volume (%)	Geometry
Circular microstructure	0.017020	0.0200	1.10	
Channels	1.5064934	1.80954	98.90	
Moulding complete	1.5235134	1.82954	100	

Moldflow Plastic Insigth 5.0 was used to simulate the process of injection molding of the lens. The simulation was discretized with 30810 triangular elements and 15409 nodes throughout the set. The three-dimensional model of the molded part includes two cavities symmetrically arranged, injection point, sprue and well. The model generated is shown in Fig. 6.

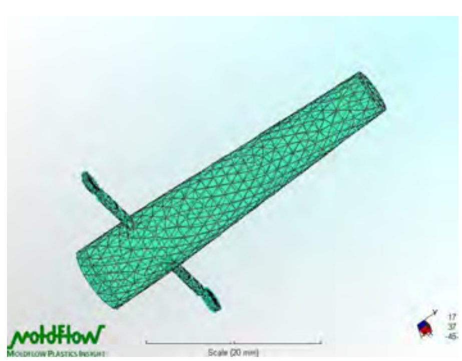


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Figure 6. Finite element mesh of the three-dimensional model including cavities, channels and well.

The analysis of the filler in the program Moldflow Plastics Insight 5.0 was taken in order to verify not only the filler but also the conditions of pressure and temperature of the melt, the existence and location of prison air. Filling was obtained in a time of 0.8142 sec. This option increased the injection rate, which is desirable because it reduces the contact time between the polymer and the wall of the mold cavity avoiding anticipated cooling and injection incomplete. The pressure reached in filling in the time of 0. 8142 sec is within the expected and experimental values obtained by other authors for structures with characteristics similar to those simulated in this this job. In filling analysis was possible to obtain the maximum value for the injection pressure of 50.09 MPa, where the equipment in this respect, meets the requirements.

The melt temperature is the energy that is transported through a particular location. The temperature of the melt not only changed with time and place, but also the thickness for the entire cycle of injection molding. It is difficult to illustrate all these changes in a single graph. As a result, the overall temperature is used to indicate the weighted average temperature throughout the thickness of the dough. The temperature of the mass has the physical meaning as the average temperature of the molten polymer flows. The maximum temperature of the mass is near the thermal degradation of the polymer should reconsider the part geometry or change the process conditions. Differences very close to these temperatures can also cause non-uniform shrinkage and warpage of the product. The simulation showed that the temperature of the end of the filling mass was 213.9 °C.

The apparatus used in this work provides temperatures over four regions, from the beginning of the thread to the point of injection during lamination. In the injection process the samples in this study were the following values adopted for these regions: Z1 = 195 °C, Z2 = 200 °C, Z3 = 205 °C; injection nozzle = 210 °C. The temperature at the flow front is the value reached by the polymer under a specified node. This can be at the end or at specified intervals during the analysis. If the temperature of the flow front is low in an area of the piece, the filling material failure may occur. In areas where the temperature is very high degradation of the material and surface defects may occur. In the numerical simulation, the temperature of 210.1 °C remains constant during filling, which provides good results in the process.

The evaluation performed by using the Moldflow software, allows to foresee the complete filling of the cavities. However, it was observed that injection pressure did not need to be as high as envisaged in the simulation filler (55.09 MPa). With the pressures that were used at all stages, the wells should not present insufficient material during injection that could affect the process. The literature considers that for the injection of microstructures with aspect ratios greater than 1, the injection pressures must lie above 100 MPa (Rosato et al, 2000). The preliminary adjustment of the equipment had on the parameters obtained in the numerical simulation. Thus the conditions are chosen to impart starting the most appropriate procedure or injection temperature of 210 °C, mold temperature 90 °C and filling time of 0.8 sec. Using inserts lenses with circular structure, to evaluate the relation between surface conditions and molded injection process, variations were made in injection pressure and mold temperature. The other parameters remained unchanged as shown in Tab 3.

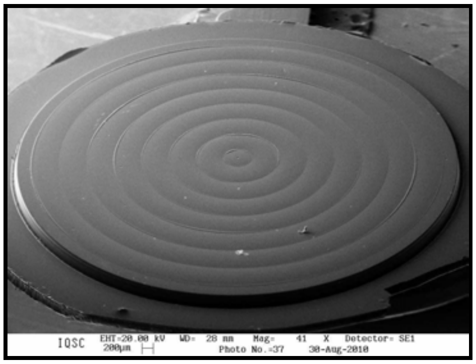
Table 3. Injection parameters.

Test	**Injeçtion temperature (°C)**	**Injection speed (mm/sec)**	**Injection time (sec)**	**Injection pressure (bar)**	**Mold temperature (°C)**
1	210	115.5	0.8	70	85
2	210	115.5	0.8	100	85
3	210	115.5	0.8	130	85
4	210	115.5	0.8	130	100
5	210	115.5	0.8	130	115
6	210	115.5	0.8	130	130

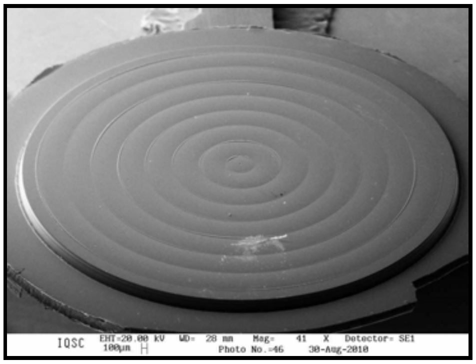
Was investigated mainly the relationship between the surface roughness and profile of the components injected. To evaluate the shape and surface integrity of the mold cavities and the molded lens was used Veeco Optical Profilometer, model NT 11000.

3. EXPERIMENTAL ERESULTS

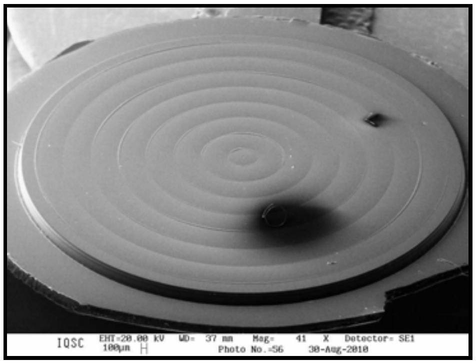
Images of scanning electron microscopy, the Fig 7, show tests conducted with a temperature of 85 °C and injection pressures of 70, 100 and 130 bar. The dark spots in (c) represent fragments of micro partially molten polymer deposited on the structure.



(a)
$P_{injeçtion}$ = 70 bar



(b)
$P_{injection}$ = 100 bar



(c)
$P_{injeçtion}$ = 130 bar

Figure 7. SEM photomicrographs taken through the lens structure with circular injected T_{mold} = 85 °C and injection pressures varied. Lens diameter of 8 mm. Magnification: 41X.

Figure 8 shows that the lower roughness values were obtained with the injection pressure of 70 bar.

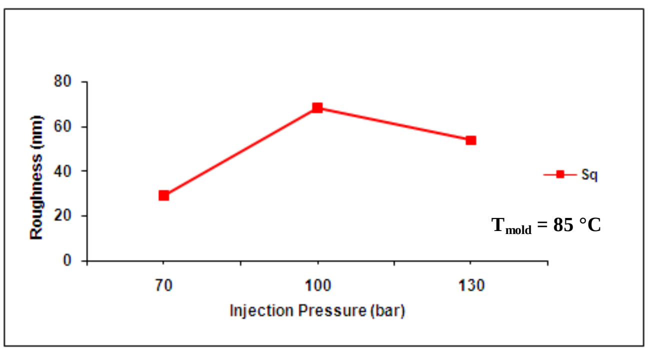


Figure 8. Variation of Sq roughness in relation to injection pressure in circular microstructure.

The 3D profilometry lens surface, Fig.9 (a), generated the parameter of 19.47 Sq nm optical surface roughness related in (b). This value is compared with the roughness Sq = 19.03 nm, obtained from profilometry of the insert before the injection process shown in Figure 5 (b) results in a difference of 0.44 nm reflects the excellent replication process. In (c) shows the profile of the step value 0. 5010 mm, the structure replicated. The value of this parameter related to the profile of the insert shown in Fig. 5 (a) is 0. 5054 mm resulting in a difference of 0. 0044 mm.

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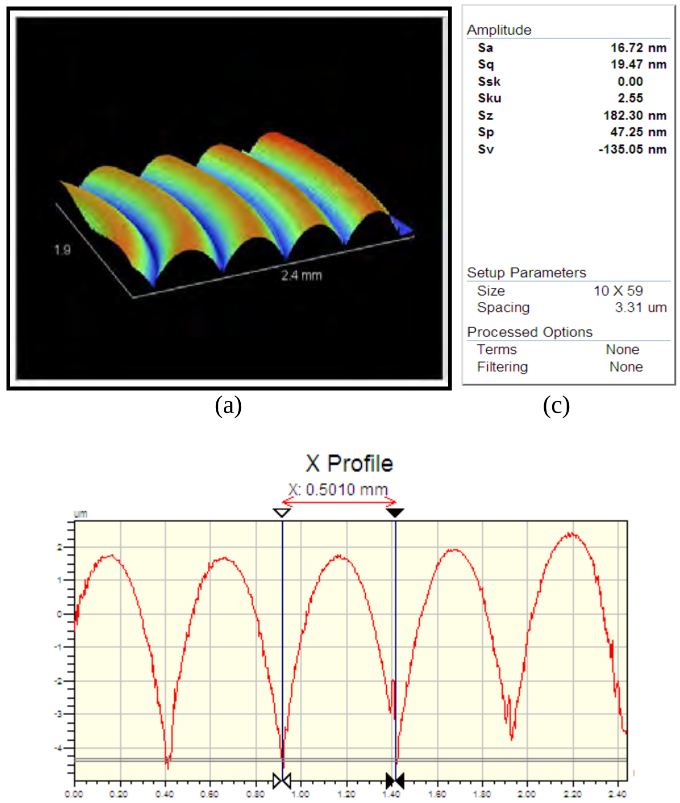
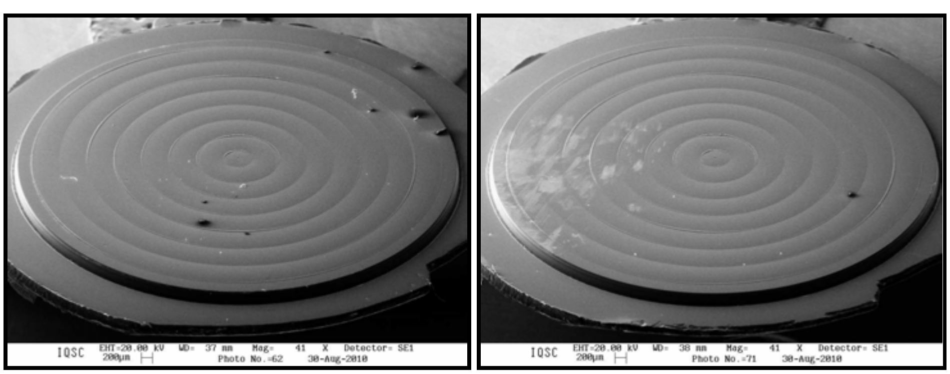


Figure 9. Optical profilometry microstructure circular injected with variation of injection pressure. (a) Profile 3D lens. (b) Roughness (c) Profile of the structure.

In another test with the injection pressure constant at 130 °C mold temperature was varied at 100, 115 and 130 °C. The lenses obtained in this condition resulting from scanning electron microscopy can be seen in Fig. 10. The dark spots and white spots that appear on the surface of the lens in the figure are contaminations that may result from degradation or contamination of the material, as well as mold cleaning



(a) T_{mold} = 100 °C

(b) T_{mold} = 115 °C

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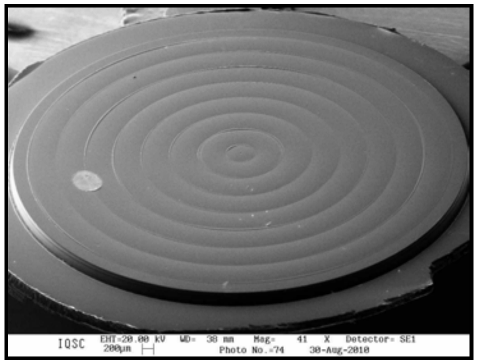


(c)
T_{mold} = 130 °C

Figure 10. SEM photomicrographs of circular microstructure injected with $P_{injection}$ = 130 bar. Lens diameter of 8 mm. Magnification: 41X.

Figure 11 shows lower values of surface roughness were obtained considering a mold temperature of 100 °C, this temperature which is 9 °C below the Tg of the polymer.

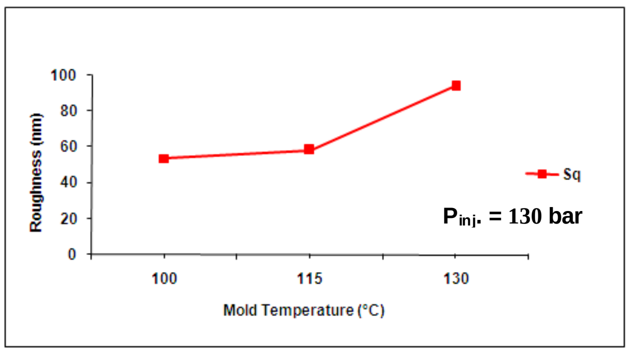
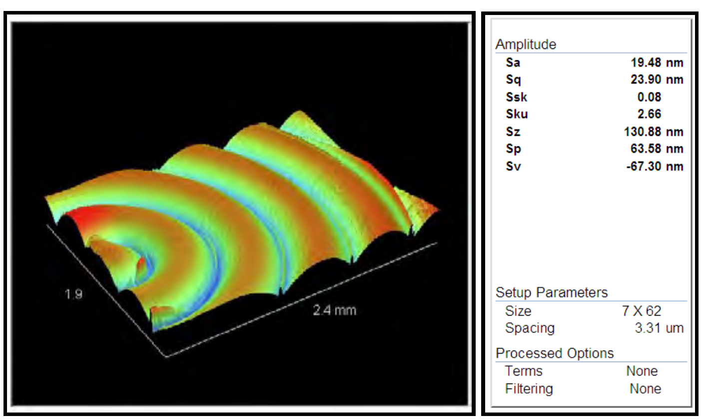


Figure 11. Variation of surface roughness versus mold temperature.

Through the lens of the 3D surface Fig. 12 (a) was obtained Sq parameter is 23.90 nm optical roughness as shown in (b). The roughness Sq = 19.03 nm, obtained from profilometry of the insert before the injection process previously shown in Fig. 5 (b) resulted in an increase of 4.87 nm between the mold and the replica, which is not significant for the process. The pitch value of 0.5044 mm replicated structure is shown in (c). The pitch value for the insert as shown in Fig. 5 (c) is 0.5054 mm, with a deviation in the spacing of 0. 0010 mm, considered negligible.



(a) (b)

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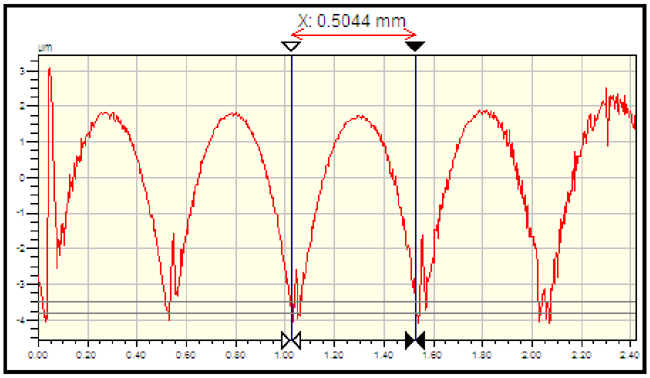


(c)

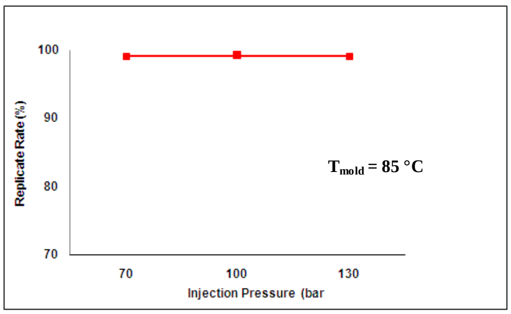
Figure 9. Optical profilometry of circular microestruture injected with variation of the mold temperature. (a) 3D profile of the lens. (b) Roughenss (c) Profile structure.

Analyzes related to the degree of replication of the microstructures shown in the above study can be seen in the charts below where the replication rate was calculated from Eq (1), suggested by Yamada et al (2008). This study considered the pitch of circular structure

$$\frac{H_i}{Hr} x100(\%) \text{ where,} \qquad (1)$$

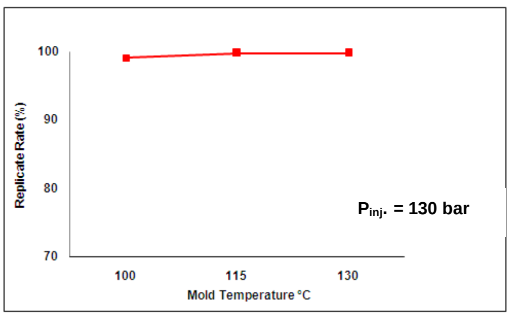
H_i = Height of the insert
H_r = Height of the structure replicated

The rate is dependent on the replication process variables, with mold temperature and injection pressure were studied remained nearly constant. In both conditions studied replication rates were between 94 and 99%, meaning that the parameters involved in the casting process are provided a great degree of replication. Circular replicated microstructure was examined the reproducibility of the pitch size. The graph of Fig. 10 (a) was varied in the case where the injection pressure, it can be seen that the curve is constant due to the degree of replication obtained of 99%.



(a)

Similarly in Fig. 10 (b) the replication rate remained almost constant at 99%, assuming now the condition where the mold temperature was varied, and the injection pressure maintained at 130 bar.



(b

Figure 10. Replication rate of the pitch circle of the microstructure with respect to: (a) Injection pressure (b) Mold temperature

4. CONCLUSIONS.

The main objective of this research was to analyze the process of injection molding for replication of micro optical element polymer. This research includes learning about the process of micro injection molding, its ability to reproduce the characteristics of small lenses and their limitations. Factors such as mold temperature and injection pressure were studied. This understanding was developed through experimental tests and numerical simulation. As the concepts applied in this study are different from those used widely in conventional injection molding, due to little information nationally, both in industry and in academia, the results of the experiments can be considered satisfactory and show that:

It is possible to obtain polymeric microelements injection molded, high quality and precision optics, using molds machined monocrystalline diamond tool, where the reduction of cost of production for the manufacture of molds and molding the lens is very important factor.

The process is capable of replicating micro-optical components in high volume production with low cycle times of injection. The lenses of this research were molded with injection time of 1 second and constant injection speed of 115 mm / s.

Although the values of the roughness of the insert and the replicated lenses have been higher than expected for optical surfaces, where it is recommended to be in the range 5-10 nm, the experiments showed good fidelity replication.

Although the tests performed has been observed that the temperature of the mold together with the injection pressure influence the quality of the molded surface, it can be considered that condition alone, whereas other parameters, such as closing pressure, injection time and injection speed can also affect the results.

The degree of replication of the injected lens indicates that the process conditions were appropriate. Due to the characteristics of the structure of the wavefront sensor to facilitate the movement of molten polymer in the cavity even with the temperature below the Tg was observed that the degree of replication was constant at 99% by varying the injection pressure

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